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How common are Earth-Moon planetary systems?

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Abstract. The Earth's comparatively massive moon, formed via a giant impact on the proto-Earth, has played an important role in the development of life on our planet. Here we study how frequently Earth-Moon planetary systems occur. We derive limits on the collision parameters that may guarantee the formation of a circumplanetary disk after a protoplanet collision that could form a satellite. Based on a large set of simulations, we observe potential moon forming impacts and conclude that giant impacts with the required energy and orbital parameters for producing a binary planetary system occur frequently with more than one in ten terrestrial planets hosting a massive moon.

Keywords. planets and satellites: formation

Our main purpose is to explore the giant impact history of terrestrial planets in order to calculate the probability of having a large Moon-like satellite companion. A giant impact between a Mars-size proto-planet and the proto-Earth is the accepted model for the origin of our Moon (e.g. Hartmann & Davis 1975; Cameron & Benz 1991). After its formation, the Moon was much closer and the Earth was rotating more rapidly. The large initial tidal forces created high tidal waves several times per day, possibly promoting the cyclic replication of early biomolecules (Lathe 2004) and profoundly affecting the early evolution of life. Today, the Moon stabilizes the spin axis of our planet (Laskar *et al.* 1993). A stable spin axis and therefore a stable climate on timescales of more than a billion years may be essential to guarantee a suitable environment for, in particular, land-based life.

A large set of N-body simulations, where Earth-like planets in the habitable zone form, provides the background of our study (Morishima *et al.* 2010). This simulations take into account gravitational accretion and hydro-dynamical processes in the planet formation process. The collision parameter space that describes a giant impact is given by the ratio of impactor mass to total mass in the collision, by the impact velocity, by the impact parameter and the total angular momentum. If one does not focus on a strongly constrained system like the Earth-Moon system but just on terrestrial planets of arbitrary mass with satellites that tend to stabilize their spin axis, the parameter space is broad. It becomes difficult to draw strict limits on the parameters because collision simulations for a wider range of impacts were not available for our study. Hence, starting from published Moon-forming SPH simulations by Canup (2008), we derive scaling relations to estimate rough limits on a parameter space that guarantees a circumplanetary debris disk that can form a satellite outside the Roche limit, including obliquity stabilization and tidal evolution.

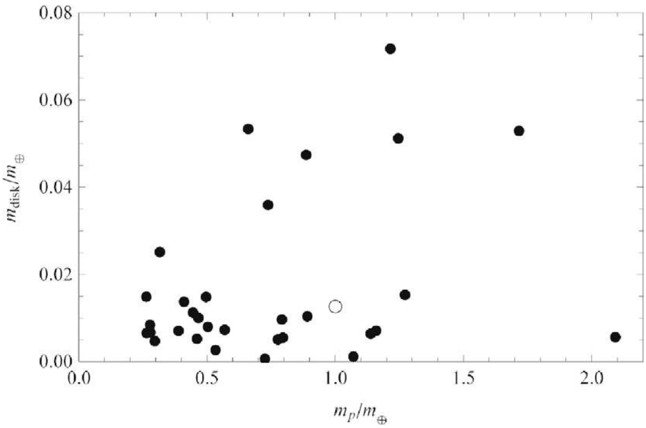

Figure 1. The masses of the final outcomes of the planets for which we identified satellite forming collisions. $m_{\rm disk}$ is the mass of the proto-planetary disk, which is an upper limit on the satellite mass, and m_p is the mass of the planet after the complete core accretion. The circle indicates the position of the Earth-Moon system with the assumption $m_{\rm disk} = m_{\rm Moon}$. Since we exclude collisions of the small initial planetesimals in the simulation from consideration for satellite forming events, there are only few small disks.

Under rather restrictive conditions, we identify 31 moon forming events in 64 simulations, the masses of the resulting planet-satellite systems are shown in figure 1. On average, every simulation gives three terrestrial planets with different masses and orbital characteristics. Hence, at least one of six planets has an obliquity stabilizing satellite in its orbit. If we focus on Earth-Moon like systems, where we have a massive planet with a final mass larger than half of an Earth mass, we identify 19 moon forming collisions. Therefore, one in ten planets has a satellite, for which five out of six of those satellites are larger than half a Lunar mass. The mass of a satellite in our study is clearly overestimated since we equate it with the mass of the circumplanetary disk mass, but it shows that there are not only a few small satellites.

Life on planets without a massive stabilizing moon would face sudden and drastic changes in climate, posing a survival challenge that has not existed for life on Earth. Our simulations show that planets with massive moons occur quite frequently.

References

Cameron, A. G. W. & Benz, W. 1991, *Icarus*, 92, 204
Canup, M. R. 2008, *Icarus*, 196, 518
Hartmann, W. K. & Davis, D. R. 1975, *Icarus*, 24, 504
Laskar, J., Joutel, F., & Robutel, P. 1993, *Nature*, 361, 615
Lathe, R. 2004, *Icarus*, 168, 18
Morishima, R., Stadel, J., & Moore, B. 2010, *Icarus*. 207, 517